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Natural resource demand of global biofuels in the Anthropocene: A review

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ABSTRACT

The Anthropocene is the later part of the Holocene where human activity has become a major driver for global ecosystem development. The demand of natural resources, renewable and non-renewable, is a crucial aspect of environmental (un-) sustainability. When considering a societal transition scheme towards sustainability, bio-based options come to the fore. The article develops a global framework for the analysis of natural resource demand of global biofuels. The framework defines the biofuel system in terms of exergy at four levels, i.e., the foreground system, the supply chain, the anthroposphere, and the ecosphere. Various measures of resource demand, such as cumulative exergy demand, global and anthropogenic exergy budgets are incorporated into the framework. Based on reviews of global biofuel production and natural resource demand of the anthroposphere, the study finds that the production of conventional biofuels, i.e., first generation of biodiesel and bioethanol by key producer countries in 2008 consumed 9.32 E+11 MJ of exergy from non-renewable resources and accounted for 0.23% of the total anthropogenic non-renewable resource demand. In addition, it shows that the contribution to climate change due to the heat emission of the global biofuel production was 5.79 E−05 W/m^2, which would reach up to 0.002% of global greenhouse warming if anthropogenic heat flux is treated as a climate forcing.

Contents

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1. Introduction

1.1. Biofuels in the Anthropocence

We are currently in the era sometimes called the Anthropocene, in which humanity and human activities have become a global geophysical force and the main drivers of global environmental change [1,2]. The historical development of primary energy supply for humanity can be taken as a typical example. Prior to the Anthropocene, biomass, together with peats, satisfied nearly all energy demands, and there was hardly any consumption of fossil fuels (except for coal), uranium ore, geothermal heat, or the moon's gravitational energy. With industrialization, human consumption of non-renewable energy sources, mainly fossil fuels, outpaced that of renewable energy sources. Since WWII, human society has witnessed a dramatically increasing consumption of fossil fuels and fission energy. In recent decades, human concerns about increasing oil prices, energy security, and global warming are motivating the utilization of renewable energy sources which accounts for the minority of the current total primary energy production. The use of biofuels, i.e., fuels derive from biomass, for transportation is already being promoted as a (supra-) national policy, for instance in the United States (Energy Independence and Security Act of 2007 [3]) and in Europe (Directive 2003/30/EC [4]). The global biofuel production totaled 7.80 E+07 m^3 in 2008 [5] and provided 1.8% of total transport fuels in 2007 [6].

Biofuels are commonly produced from plants, animals, and micro-organisms but also from organic wastes. They can be solid like biochar, liquid like biodiesel and bioethanol, or gaseous like biogas, biosyngas and biohydrogen. The biggest difference between biofuels and petroleum feed-stocks is oxygen content [7]. The current global biofuel economy is an aggregation of a dozen of national markets. Each market provides various kinds of biofuels in terms of different feed-stocks of biomass, agricultural cultivation methods, industrial conversion technologies, and the process energy to power the industrial conversion. Liquid biofuels, mainly biodiesel and bioethanol are considered as promising fuel alternative to petroleum-derived fuels. Biodiesel is monoalkyl esters of long chain fatty acids derived from vegetable oil or animal fat. Bioethanol is ethanol derived exclusively from the fermentation of plant starches.

1.2. Environmental (un-) sustainability of biofuels

Like any other energy- or material-based products, the production of biofuels requires non-renewable resources in its supply chain before biofuels enter the anthroposphere for further utilization. For the environmental aspect of sustainable development, natural resources, i.e., any form of energy or materials from the ecosphere that is required to deliver products and meet human needs in the anthroposphere, should not run out and emissions, mainly in terms of heat and waste, from the anthroposphere should not endanger the ecosphere or transcend the ecospherical carrying capacity [8,9]. With regard to the environmental sustainability of biofuel technological system, most attention has typically been focused on land and water requirements [10], the energy balance [11,12], net greenhouse gas emissions [12,13], and recently on local climate impacts caused by land-use change [14,15]. Few tackle the demand of natural resources such as primary energy and raw materials or the climate impact due to heat emission.

The study aims at addressing the question how the natural resource demand of biofuel technological system can be analyzed to assess its environmental sustainability. A global framework for the analysis is developed and exergy is introduced as a measure of the resource value. The main context of the study is organized as follows. In Section 2, we describe the systems diagram, the exergy-based resource measure, and the data sources. Sections 3 and 4 present the review of the global biofuel production in 2008 and the natural resource demand of the anthroposphere, respectively. In Section 5, we compare the results of the reviews and discuss the implication of heat emission and entropy generation. At last, Section 6 gives the main conclusions of the article.

2. Materials and methods

In this section, we define the framework of analysis, discuss the metrics that are to be studied, and describe the data sources used.

2.1. Systems diagram

The principle of system definition is that it should include all relevant processes. Fig. 1 shows the four different levels of system boundary, labeled A, B, C, and D of the conceptualized biofuel technological system.

Level A (the ecosphere) principally includes the planetary processes that provide renewable resources, i.e., natural resources that are generated on a human time scale (tidal, biomass, solar, hydro, wind, geothermal, and wave), and non-renewable resources, i.e., resource stocks that have been accumulated on a geological time scale (fossil and nuclear fuels, metal ore, and mineral stocks). Level B (the anthroposphere) includes all the human activities, mainly production and consumption processes. Level C (the supply chain) includes part of the production and consumption processes that supplies the intermediate products. Level D (the foreground system) is defined to only account the direct inputs of the foreground processes, such as agricultural production and industrial conversion to deliver biofuels (see Fig. 2 for an exemplified diagram of the bioethanol produced from corn stover at level D [16–18]).

2.2. Exergy-based resource measure

2.2.1. Exergy

Exergy is defined as the maximum amount of work that can be obtained from a flow of energy or materials when it is brought into equilibrium with a reference environment (for a commented history of the concept, see Sciubba and Wall [19]). It has the same unit as energy, i.e., Joules. This study adopted the reference environment proposed by Szargut et al. [20,21], which is defined as the global average environment that has average chemical compositions of the atmosphere, seawater, and the crust under temperature of 298 K and atmospheric pressure of 1.01325 E+05 Pa. Exergy can be a proxy of the physical value of a resource since all production and consumption processes in the anthroposphere require energy and material resources from the ecosphere that feature exergy. Exergy

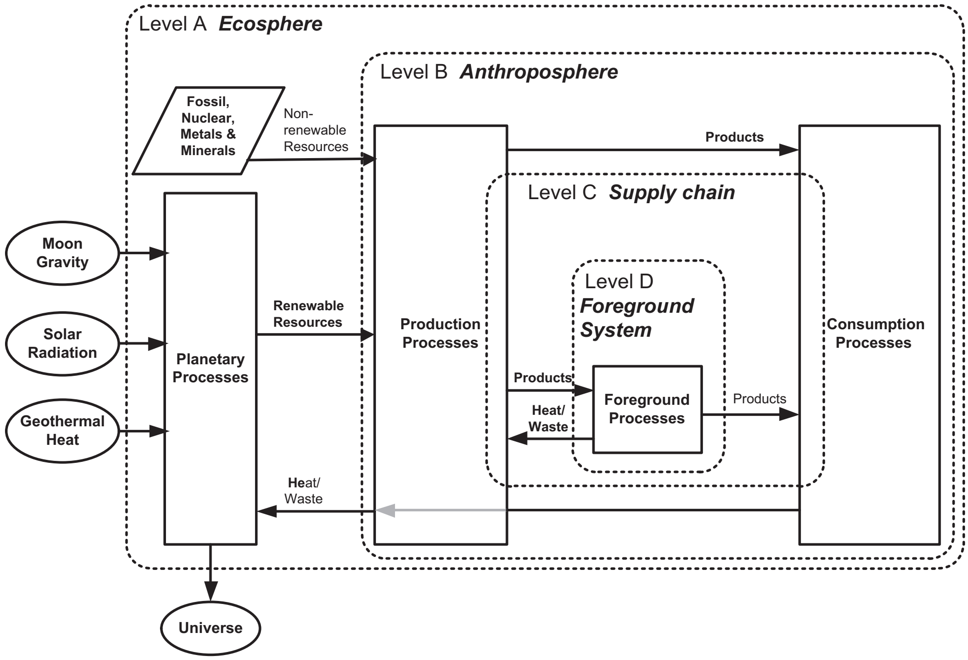


Fig. 1. Systems diagram of resource demand analysis of energy-/material-based products. The ellipses stand for sources or sinks, the parallelogram for stocks, and the rectangles for processes, i.e., conversion steps. Dashed lines represent the boundaries of the levels of analysis.

is consumed in all real processes. The exergy being consumed is in proportion to the entropy being generated. Exergy analysis can inherently measure exergy consumption (i.e., losses) and is being applied in various fields, including industrial and engineering models, economics, environmental impact assessment, systems ecology, and societal systems [19,22–24].

2.2.2. Cumulative exergy demand

Cumulative exergy demand (CExD) expresses the gross exergy of all natural resources required to deliver a product [25]. CExD is equivalent to the definition of cumulative exergy consumption of Szargut [21]. In Fig. 1, CExD measures the exergy value of all renewable natural resources and non-renewable natural resources at the interface of level A and level B that are needed to deliver the final product at level D. This study defines the cumulative exergy demand of non-renewable natural resources, i.e., energy resource including fossil fuels (F) and nuclear fuels (N), and material resources including metal ores (O) and minerals (M), as $\mathrm{CExD_{NRR}} = m_O\alpha_O + m_M\alpha_M + n_F\beta_F + n_N\beta_N$, where "$m$" stands for the mass of a material resource in kg, "α" for the chemical exergy density of a material resource in mega-joules (MJ), "n" for the amount of energy from an energy resource in MJ, and "β" for the exergy-to-energy ratio of an energy resource.

2.3. Data sources

Data used in the study were obtained from various sources. Data on the biofuel production capacity of key producers were collected from a report to the International Energy Agency (IEA) Bioenergy Task 39 [5] and reconciled with a report to the United Nations Environment Programme (UNEP) by the International Panel for Sustainable Resources Management [6], a special report on renewable energy resources by the Intergovernmental Panel on Climate Change (IPCC) [26], and various literature values [27–31]. Data of the cumulative amount of energy and mass required for a specific biofuel was exported from ecoinvent database of the Swiss Centre of Life Cycle Inventories [32] or approximated by associating the β-value of an energy resource with the cumulative degree of thermodynamic perfection of the corresponding intermediate products [20,21,33]. Data gaps were partially filled by making various assumptions. Besides, wherever possible the data were collected for the year 2008, unless as noted specifically.

3. Review of global biofuel production

The current global biofuel production is primarily based on the first generation/conventional technologies, i.e., using sugar, starch, and vegetable oil as feed-stocks. Production of advanced biofuels, i.e., biofuels derived from non-food crops and algae, has not taken place on a large scale yet. In 2008, the global production of liquid biofuels for transport was dominated by a dozen of countries: the US, Brazil, China, Canada, Australia, Japan, and some EU member states. Below we briefly discuss the situation in these countries.

3.1. United States

Ethanol derived from corn grains is the primary biofuel used in the US. In 2007, the US used 24% of its national corn harvest to produce bioethanol. More than 200 bioethanol production facilities have been built in the US since 1976, which produced 3.63 E+07 m^3 of ethanol in 2008. Biodiesel use has also risen, with about 2.65 E+06 m^3 of production from soya and sunflower in 2008. A Renewable Fuel Standard legislated as part of the Energy Independence and Security Act of 2007 requires 1.36 E+08 m^3 of biofuels, including both conventional and advanced biofuels in traffic fuel mix by 2022. Advanced biofuels production, as required by the Act, is expected to increase dramatically, and would exceed conventional biofuels production by 2021.

3.2. Brazil

Ethanol derived from sugar cane is the primary biofuel produced in and exported from Brazil which firstly widespread developed the biofuel market. In response to the first oil crisis of the 1970s, Brazil lunched the National Ethanol Program, Proálcool. Several

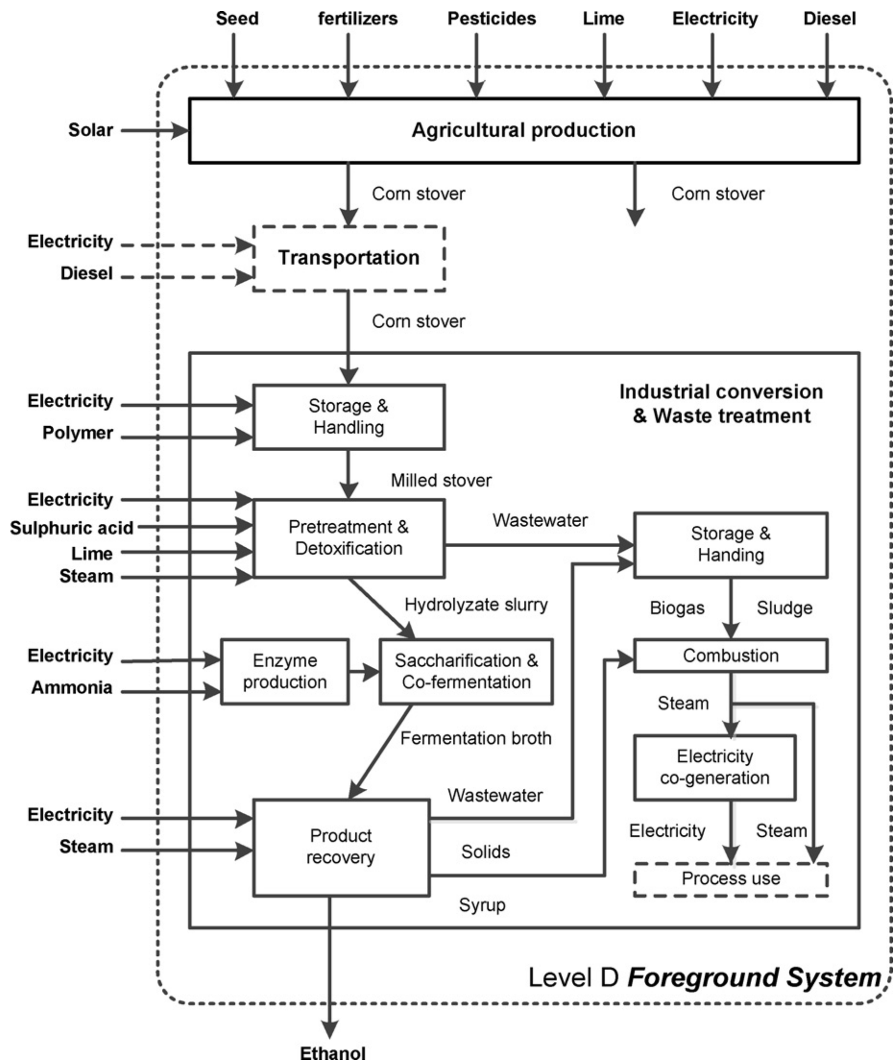


Fig. 2. Systems diagram of the foreground processes at level D, ethanol production from corn stover (modified after [16,17]). Nomenclature for the diagram can be found in [18].

policies were introduced to promote biofuel consumption. Price regulations were removed in the late 1990s. In 2008, the existing 248 plants produced 2.45 E+07 m^3 of ethanol, about 3.50 E+06 m^3 of which were exported to the US, Europe, Korea and Japan. Biodiesel production was at a record level in 2008 of 1.10 E+06 m^3.

3.3. China

The production of biofuels, primarily bioethanol in China has developed rapidly since 2000. By 2008, China had built five state certified fuel ethanol pants and reached a production capacity of fuel ethanol about 2.45 E+06 m^3, ranking as the third-largest single bioethanol producer after the US and Brazil. 80% of the fuel ethanol was made from corn, the rest from wheat. Due to the lack of eligible vegetable oils and a standard of biodiesel use, biodiesel production in China has been limited at a minimal level compared to the ethanol production. An estimated biodiesel production of 6.00 E+04 m^3–3.40 E+05 m^3 was reported [5], with soybean and other waste vegetable oil used as feed-stocks. However, due to the shrinking stock of inferior corn the government is seeking other biomass feed-stocks, such as cassava or sweet sorghum which may have to be imported from neighbor countries.

3.4. EU member states

The EU Directive 2003/30/EC [4] requires a minimum of 2% biofuel in transport fuels beginning 2005. The updated same directive sets a 5.75% target for 2010. By 2020, the target is projected to 10%. Because the 5.75% target has not been reached so far, the EU will have to increase its biofuel production or even focus on imports to meet this goal.

The EU Directive, the Biofuel Quota Act, and other policy initiates promote the production and use of transport biofuel in Germany. Despite the peak-and-decline biofuel market because of the removal of policy incentives happened in 2007, Germany remains its leading producer in biodiesel production, and reached a production capacity of 3.18 E+06 m^3 of rapeseed-derived biodiesel in 2008. The production of bioethanol of 7.30 E+05 m^3 is mainly from sugar beet and wheat.

France is the second largest biofuel producer in the EU, encouraging production and consumption of biofuels with tax rebates and penalties. In 2008, the production capacities were 9.91 E+05 m^3 of biodiesel from rapeseed (75%) and soybean (25%) and 5.78 E+05 m^3 of bioethanol from sugar beet (80%) and wheat (20%), respectively.

For other EU member states, viz., Spain, the Netherlands, the UK, Austria, Poland, Portugal, Ireland, Belgium, Denmark, Norway,

Table 1
Summary of production capacities of key biofuel producers in 2008, in E+03 m^3/yr.

Producer	Biodiesel				Bioethanol					
	Soybean	Rapeseed	U.S.[a]	Total	Corn	Sugar cane	Wheat	Sugar beet	U.S.[a]	Total
USA	2650			2650	36,300					36,300
Brazil	1100			1100		24,497				24,497
China	60			60	1958		490			2448
Germany		3180		3180				730		730
France	248	743		991			116	462		578
Spain		926		926			578			578
Netherlands		1372		1372						0
UK		347		347	153					153
Austria			252	252					13	13
Poland			91	91					151	151
Portugal			227	227						0
Ireland		63		63			85			85
Belgium			108	108						0
Denmark			103	103						0
Norway			39	39						0
Finland				0					3	3
Canada		60	40	100	670		200			870
Australia			260	260		64	100			164
Japan	10			10						0
Total	4068	6691	1120	11,879	39,081	24,561	1569	1192	167	66,570

[a] U.S.: unspecific feed-stocks.

and Finland, we refer to Table 1 for the review of their production capacities in 2008.

3.5. Canada

The Clean Air Act passed on late 2006 also services as a biofuels policy initiative and regulates and funds the biofuel development. Canada produced about 9.70 E+05 m^3 of biofuels in 2008, more than a four-fold increase in three years. 6.00 E+04 m^3 of biodiesel was produced from rapeseed; 4.00 E+04 m^3 from unspecific feed-stocks. The production of bioethanol was 6.70 E+05 m^3 from corn and 2.00 E+05 m^3 from wheat.

3.6. Australia

Biodiesel production in Australia was 1.00 E+05 m^3 from tallow (animal fat), 1.60 E+05 m^3 from other unspecific feed-stocks in 2008. The bioethanol production was 1.00 E+05 m^3 from wheat and 6.4 E+04 m^3 from sugar cane and cane molasses (residues).

3.7. Japan

Though being a main economic power, Japan has fairly low biofuel production. The most widely used biofuel, ethyl tert-butyl ether, is totally imported. Domestic biofuel production is beginning. In 2008, 1.00 E+04 m^3 of biodiesel was produced from soybean for traffic use. And there is no ethanol produced domestically.

3.8. Synthesis

To sum up, as shown in Table 1, biofuel production capacity in 2008 across the 19 countries under consideration in the study totaled 1.19 E+07 m^3 of biodiesel and 6.66 E+07 m^3 of bioethanol. Over 99% of the production has been based on the first generation/conventional technologies.

4. Review of anthropogenic exergy resource demand

4.1. Ecosphere

As shown in Fig. 1, solar radiation, moon gravity, and geothermal heat are three main primary energy and exergy sources supporting all the planetary processes. The exergy of solar radiation received by the Earth can be easily approximated once the solar constant, i.e., the flux density of solar radiation received by the Earth, is determined and related to the β-value given by Petela [34]. Part of the exergy reaching the Earth is immediately reflected and backscattered by the atmosphere. A small percent of the incident exergy is reflected by the Earth's surface as well. Moon gravity, together with solar gravity interacts with the rotating Earth and causes tides as the motion of sea levels. Tidal exergy dissipates as friction in the shallow oceans and continental shelves, 70% of which is attributed to the moon gravity. Specific tidal exergy is equivalent to the gravitational potential energy due to the height difference between the tidal maxima and minima over the tidal record [35]. Geothermal energy to the ecosphere comes from three sources, i.e., lithospheric heat, heat from the core, and heat from radioactive decay. Conversion of these energy flows into exergy flows depends on the Carnot efficiency that in turn is determined by the temperature of a geothermal heat flow and the temperature of the reference environment. The uncertainty of various geothermal heat flows makes the determination of global geothermal heat quite challenging. The evaluation of other exergy sources, i.e., solar radiation and moon gravity, is characterized by different uncertainties due to the lack of sufficient knowledge of the dynamics of the complex ecosphere. Hence various estimations of global exergy sources are reported which are summarized in Table 2 [36–45].

Table 2
Summary of various estimations of global primary exergy sources, in MJ/yr (into level A).

Primary exergy source	Reported estimation[a]	References	This study
Solar radiation[b]	3.33 E+18	[36]	3.6 E+18
	3.38 E+18	[37]	
	3.83 E+18	[38]	
	3.88 E+18	[35]	
Moon gravity	7.6 E+13	[37]	9.5 E+13
	8.5 E+13	[39]	
	9.5 E+13	[38]	
	1.17 E+14	[40,41]	
Geothermal heat	9.78 E+14–1.104 E+15	[42,43]	1.198 E+15
	1.325 E+15–1.388 E+15	[44,45]	

[a] Notations such as "E+18" mean exponents (10^{18}).
[b] The exergy input of net solar radiation to the ecosphere.

Table 3
Summary of global energy flows to the anthroposphere in 2008, in MJ/yr (from A to B).

Exergy resource	Energy flow[a]	β-Value[b]	Exergy consumption
Coal	1.262 E+14	1.04	1.313 E+14
Oil	1.578 E+14	1.03	1.625 E+14
Gas	1.01 E+14	0.94	9.49 E+13
Nuclear	2.59 E+13	1	2.59 E+13
Geothermal	8.8 E+11	0.71	6.25 E+11
Tidal	1.6 E+10	1	1.6 E+10
Hydro	1.26 E+13	1	1.26 E+13
Biomass	5.36 E+13	1.05	5.63 E+13
Wind	1.9 E+12	1	1.9 E+12
Solar[c]	5.4 E+11	0.93	5.0 E+11

[a] Energy flow values are from the International Energy Agency (IEA)[46] and the British Petroleum (BP) [47].
[b] β-Values of non-renewable energy resources are from Szargut [33]; β-value of geothermal is based on a global average Carnot efficiency of 0.71 in Hermann [35]; other β-values are following the definition.
[c] Solar energy collected directly by photovoltaic panels and solar thermal panels.

Table 2 shows that by far the dominant primary exergy source to the ecosphere is the net solar exergy input of 3.60 E+18 MJ/yr. The other two independent primary exergy sources, i.e., geothermal heat and moon gravity, which totaled to about 1.29 E+15 MJ/yr are several orders of magnitude less than that of the net solar exergy input and thus their contribution is negligible.

4.2. Anthroposphere

The exergy demand by the anthroposphere is considerably smaller than that of the ecosphere. While the literature values of metal and mineral exergy resources are not available, Table 3 summarizes the exergy demand of the anthroposphere [21,35,46,47]. It is indicated in Table 3 and Fig. 3 that the anthroposphere mainly relies on non-renewable exergy resources, which amount to 4.15 E+14 MJ/yr and accounts for 85.2% of the global anthropogenic exergy demand. This value includes 3.89 E+14 MJ/yr from fossil fuels and 2.59 E+13 MJ/yr from nuclear fuels. It is assumed that the exergy extracted from non-renewable energy resources is completely consumed in various production and consumption processes. This corresponds to a heat of 4.15 E+14 MJ/yr added to the planetary processes.

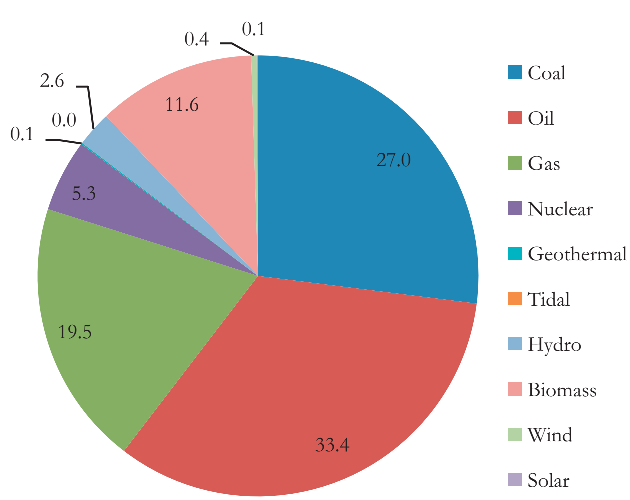


Fig. 3. Summary of global anthropogenic demand of various exergy resources, by percentage (from A to B).

Table 4
Summary of exergy resource demand of different biofuels ($CExD_{NRR}$), in MJ/yr (from C to D).

Biofuel	$CExD_{NRR}$
Soybean methyl ester	6.13 E+10
Rapeseed methyl ester	1.00 E+11
Corn-derived ethanol	6.62 E+11
Sugar cane-derived ethanol	7.36 E+10
Wheat-derived ethanol	2.82 E+10
Sugar beet-derived ethanol	7.97 E+09

5. Natural resource demand and heat emission

5.1. Natural resource demand of biofuels

The biodiesel production from soybean shares a number of processes with that from rapeseed. Inflows for the agricultural production under consideration are seeds, lime, fertilizers, pesticides, fuels for the operation of agricultural machinery, and steel for the production of agricultural machinery. Inflows for the industrial conversion are fuels, chemicals, and various feed-stocks such as soybean, rapeseed, corn, sugar cane, wheat, and sugar beet. Table 4 summarizes the cumulative exergy demand of non-renewable resources that is required in the supply chain of these inflows to deliver a specific type of biofuel.

Table 5 compares results of the natural resource demand of global biofuels with that of the anthroposphere. The normalization shows that the production of the first generation biofuels, i.e., biodiesel and bioethanol, by key producer countries in 2008 consumed 9.32 E+11 MJ of exergy from non-renewable resources and would account for 0.23% of the total anthropogenic non-renewable resource demand.

5.2. Heat emission of biofuels

Anthropogenic heat, i.e., heat generated by various human activities and emitted to the ecosphere, is neglected in current global climate models, likely because it is considered as a much smaller contributor to global warming than greenhouse gases and aerosols. However, the heat that is introduced by deriving exergy from nonrenewable resources would not otherwise have been added on relevant timescales, thus should constitute a climate forcing [48,49]. An outgoing ecospherical radiation flux of 238 W/m^2 at an equivalent blackbody temperature of 255 K is reported [38,50]. The global anthropogenic exergy demand and non-renewable exergy demand of global biofuels correspond to a heat emission to the ecosphere of 4.87 E+14 MJ/yr and 9.32 E+11 MJ/yr, respectively. With an average Earth's surface temperature of 288 K and Earth's surface area of 5.1 E+14 m^2, they generate heat flux of 0.03 W/m2 and 5.79 E−05 W/m^2 and entropy at a rate of 5.36 E + 10 W/K and 1.03 E+08 W/K, respectively, as shown in Table 6. Although the anthropogenic heat is small compared to the ecospherical radiation, its addition might lead to a new equilibrium with a higher temperature (global warming). Besides, comparing to greenhouse gases that have a climate forcing of 2.9 W/m^2 [51], the contribution to climate change of heat emission due to the exergy consumption

Table 5
Anthropogenic natural resource demand share of global biofuels.

Biofuel	$CExD_{NRR}$, in MJ/yr	$Ex_{anthro\text{-}NRR}$ [a] in MJ/yr	$CExD_{NRR}/Ex_{anthro\text{-}NRR}$
Biodiesel	1.61 E+11	4.15 E+14	0.04%
Bioethanol	7.71 E+11	4.15 E+14	0.19%
Total	9.32 E+11	4.15 E+14	0.23%

[a] Exergy of total anthropogenic demand of non-renewable resources.

Table 6
Summary of heat emission and entropy generation of the ecosphere, the anthroposhere, and global biofuels (from B to A).

System	Heat flux (W/m^2)	Entropy generation rate (W/K)	Temperature (K)
Ecosphere [38,50]	238	6.17 E+14	255
Anthroposphere	0.03	5.36 E+10	288
Biofuels	5.79 E−05	1.03 E+08	288

of global biofuels is about 0.002% of global greenhouse warming and could be negligible at level A. If one relates the entropy production to the global net entropy generation density (1.21 W/K m^2, reported by Chen [38]), the result indicates the entropy footprint in terms of an area of Earth's surface that is occupied by the technological system under consideration. For global primary energy supply and global biofuel production, their entropy footprint would be 4.37 E+10 m^2 and 8.48 E+07 m^2, respectively.

6. Conclusions and outlook

The study developed a global framework for the analysis of natural resource demand in order to address the question how the natural resource demand of biofuel technological system can be analyzed to assess its environmental sustainability. The framework defines the biofuel system in terms of exergy at four levels: the foreground system, the supply chain, the anthroposphere, and the ecosphere. Various measures of resource demand can be incorporated into the framework. Conclusions can be drawn on the basis of reviews of the natural resource demand of global biofuel production, the ecosphere, and the anthroposphere in 2008:

- First generation of biodiesel and bioethanol by key producer countries consume 9.32 E+11 MJ of exergy from non-renewable resources and account for 0.23% of the total anthropogenic non-renewable resource demand.
- The heat flux induced by global biofuel production is 5.79 E−05 W/m^2, which would reach up to 0.002% of global greenhouse warming if anthropogenic heat flux is treated as a climate forcing.
- Global biofuel production generates entropy at a rate of 1.03 E+08 W/K and would require 8.48 E+07 m^2 of Earth's surface for the disposal of entropy.

While the present study only analyzes global biofuel production in 2008, it may be extended to include time series based on various scenarios to investigate the future development of global biofuel economy in terms of the resource demand, climate impact, and its implication to the ecospherical carrying capacity.

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